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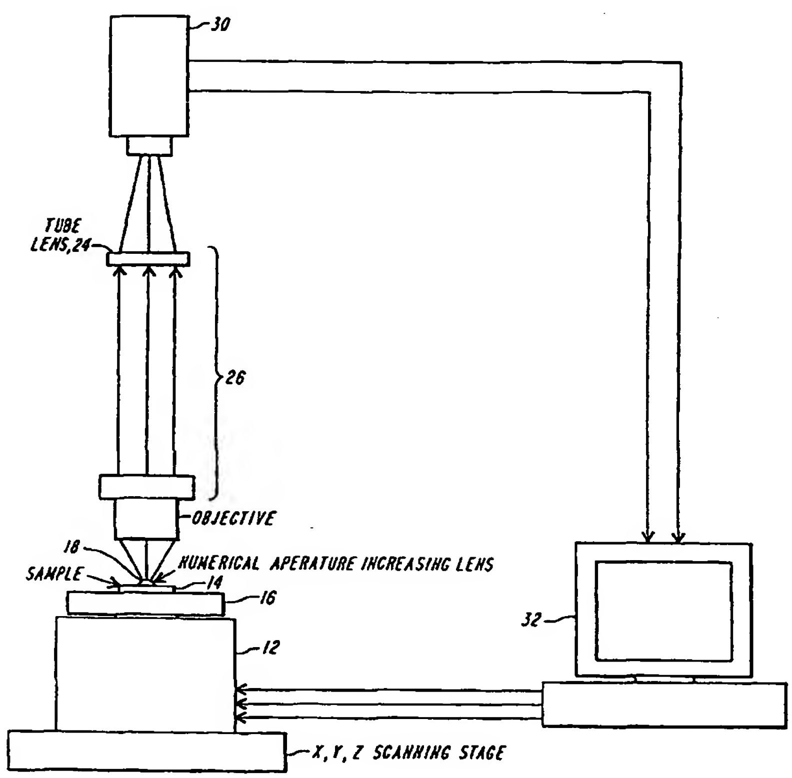
(54) Title: NUMERICAL APERTURE INCREASING LENS (NAIL) TECHNIQUES FOR HIGH-RESOLUTION SUB-SURFACE IMAGING



(57) Abstract: A viewing enhancement lens (18 - NAIL) which functions to increase the numerical aperture or light gathering or focusing power of viewing optics such as a microscope (26) used to view structure within a substrate such as a semiconductor wafer or chip or of imaging optics such as media recorders. The result is to increase the resolution of the system by a factor of between n, and n^2, where n is the index of refraction of the lens substrate.

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TITLE OF THE INVENTION

NUMERICAL APERATURE INCREASING LENS (NAIL) TECHNIQUES FOR HIGH-RESOLUTION SUB-SURFACE IMAGING

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims priority under 35 U.S.C. §119(e) to Provisional Application No. 60/140,138, filed June 21, 1999; the disclosure of which is incorporated herein by reference.

ACKNOWLEDGMENT OF GOVERNMENT SUPPORT

This invention was made with government support under Grant Number ECS-9625236 awarded by the National Science Foundation and under Contract Number 1210800 awarded by DARPA. The Government has certain rights in the invention.

BACKGROUND OF THE INVENTION

Standard optical microscopy is not capable of obtaining a transverse resolution with a definition better than approximately half a wavelength of light due to the diffraction limit, also termed the Rayleigh or Abbe limit. The diffraction limited spatial resolution is $\lambda/(2\ NA)$ where λ is the wavelength of collected light in free space. The Numerical Aperture is defined as $NA = n \sin\theta_a$ where n is the refractive index of the material and θ_a is the collection angle, the half-angle of the optical collection area. In order to improve resolution of diffraction limited microscopy the NA must be increased. The highest NA values for standard

microscope objectives in air ambient are less than *1*, with typical best values around *0.6*.

One method to increase the *NA* is to increase the index *n* of the material where the collection focus is formed. Insertion of a high index fluid, such as oil, between the microscope objective lens and the sample allows for higher *NA*, with typical best values around *1.3*. Similarly, a microscope design utilizing a high index hemispherical lens, called a Solid Immersion Lens (SIL), closely spaced to the sample can provide a resolution improvement of $1/n$. The SIL microscope relies on evanescent coupling between the light focussed in the high index SIL AND THE SAMPLE. Previous patents on SIL microscopy describe arrangements where the light is focussed at the geometrical center of the spherical surface of the SIL.

Subsurface imaging of planar samples is normally accomplished by standard microscopy. The *NA* remains the same when imaging below the surface of higher index samples, because the increase in index is exactly counterbalanced by the reduction of $\sin\theta_a$ from refraction at the planar boundary. Standard subsurface imaging also imparts spherical aberration to the collected light from refraction at the same planar boundary. The amount of spherical aberration increases monotonically with increasing *NA*. Subsurface imaging has been conducted through Silicon substrates at wavelengths of 1.0 μm and longer, with best values of transverse resolution around 1.0 μm.

The use of SIL microscopy has been suggested for subsurface imaging wherein the light phase fronts are geometrically matched to the SIL surface. However, the

method described is limited to an arrangement where a hemispherical lens collects light from a focus at the geometrical center of the spherical surface of the lens. In this case, the resolution improvement is limited to $1/n$, and the spherical aberration free area is limited to a point. An image can be formed by scanning the sample and SIL where the scan precision is relaxed by a factor of n. An image can also be formed by scanning the sample and holding the SIL stationary. The characteristics of the invention described below are an improvement over those of standard and SIL microscopy for many sub-surface applications.

BRIEF SUMMARY

The present invention provides a substrate surface placed lens for viewing or imaging to or from a zone of focus within the substrate and providing an increase in the numerical aperture of the optical system over what it would be without the lens. The enhanced numerical aperture translates into an improvement in resolution in collecting or illuminating. The focus at a specific zone within the substrate is made aberration free, providing a broad lateral extent to the field of view. Substrate and lens material are close if not identical in index of refraction, n.

The invention finds application in viewing semiconductor devices and circuits, bio/chem specimens from the underside of an attachment surface, layered semiconductor and dielectrics such as boundaries of Silicon-on-Insulator substrates, and read/write functions of buried optical media.

DESCRIPTION OF THE DRAWING

These and other features of the invention are described below in the Detailed Description and in the accompanying Drawing of which:

Fig. 1 illustrates an imaging system having a numerical aperture increasing lens (NAIL) according to the invention:

Fig. 2a is a sectional view of a NAIL and substrate in typical viewing relationship;

Fig. 2b is a sectional view of a NAIL and viewing objective for viewing into the interior of a substrate;

Fig. 2c is a sectional view of a generalized NAIL and substrate relationship illustrating a range of applications for the invention;

Fig. 3 is a sectional view of a medium illustrating the geometric and mathematical relationships of NAIL surfaces and planes of aberration free focus;

Figs. 4a- 4b illustrate additional uses for a NAIL of the invention in inspecting specimens on a bottom surface of a substrate;

Fig. 5 illustrates the application of the invention in use in specimen viewing under a cover slip;

Fig. 6 illustrates the use of the invention in the area of read/write media;

Fig. 7a - 7d illustrate actual images from the use of the invention in viewing semiconductor structure;

Fig. 8 illustrates the invention in SOI devices for boundary inspection;

Fig. 9a -9b illustrate the use of the invention in arrays;

Fig. 10 illustrates a set of NAILs according to the invention.

DETAILED DESCRIPTION

The present invention provides a viewing enhancement lens (NAIL) which functions to increase the numerical aperture or light gathering power of viewing optics such as a microscope used to view structure within a substrate such as a semiconductor wafer or chip or of imaging optics used to expose material such as data media. The result is to increase the resolution of the system by a factor of between n and n^2 where n is the index of refraction of the lens and substrate. While the lens and substrate are typically of the same index of refraction, a near match will provide similar advantages.

Fig. 1 illustrates such a viewing system in which a computer controlled XYZ motion support 12 holds a specimen 14 in a holder 16. A numerical aperture increasing lens (NAIL) 18 is placed over the specimen. The NAIL and specimen typically are polished to allow an intimate contact as free of air space as possible, at least within a fraction of a wavelength sufficiently small to avoid reflection effects at the NAIL and substrate boundary. Light from objects within the substrate 14, typically from back illumination provided by holder 16 or from surface illumination from above, passes through the NAIL 18 and thence through an objective lens 20 and exit lens 24 of a microscope system 26 into a video camera 30 or other viewing, recording or imaging element. Signals from the camera 30 are fed to a computer 32 or other processing, storage and/or viewing system for display and recordation. This allows for the recordation of a sequence of images over

time, which in turn allows for time-resolved measurements. The computer may also be programmed to operate the stage 12 for manual or automated scanning in X, Y, and/or Z to capture images over a two or three-dimensional region.

Fig. 2a illustrates a NAIL 18′ and substrate 14′ in larger scale. The NAIL 18′ typically is less than a complete hemisphere, having a vertical thickness D, and thus its center, distant from the outer surface by the radius of curvature, R, will be located within the substrate 14′ at a point 40. While the NAIL will increase the numerical aperture of the viewed objects as noted above, it is also desired to have a view which is aberration free. There is a spherical surface within the substrate, depending on its depth, at which focus occurs and aberration free viewing is obtained. This is deeper than the point 40 as explained below. There is a distance either side of this spherical surface at which the field of view is also aberration or substantially aberration free, giving a plane region where objects can be viewed with increased resolution and freedom from aberrations. With X the distance into the substrate of the field of view, then $D = R(1+1/n)-X$. Radiation phase fronts passing through the NAIL in either direction are geometrically distinct from the convex surface of the NAIL thereby providing viewing into or from a substrate depth well beyond the NAIL.

Fig. 2b shows viewing within a substrate 14′′ through a NAIL 18′′ by an objective 42 of a field of view 44 at the bottom of the substrate 14′′. The field of view can for example include the underside of processed regions of a semiconductor wafer containing

information relevant to the quality of the resulting semiconductor chip or other element. In general, as shown in Fig 2c, the NAIL 18''' and a substrate 14''' can be any elements where it is desired to view with enhanced resolution into a field of view within the substrate. Examples include microscope slide and cover glass with a NAIL on top and thermal imaging of heat emitting semiconductors in operation.

Fig. 3 is of a unitary, solid object 50, an upper part 52 of which represents the NAIL of the invention and the remainder a substrate that is to be viewed into to see a field of view at the spherical surface 54 free of aberration. An imaginary plane 58 marks the dividing line between the NAIL and the substrate. The surface 54 is defined by R/n as the depth below the center 60 of curvature of the NAIL 52.

For optimal resolution, the optics of the microscope are best matched to those of the NAIL. This is achieved when the following relation is satisfied:

$$s = (-f_1^2)/R(n+1/n);$$

where f_1 is the objective focal length, and the inter lens principle points distance (objective to exit lens principle points) = $s + f_1 + f_2$, f_2 being the exit lens focal length.

The advantage of aberration free focal points includes a region either side of the spherical surface 54 allowing plane 64, which typically contains the areas of interest, to also be substantially aberration free as shown in Fig. 3.

An additional advantage of the NAIL lens is that fewer steps are needed to build an image since the aberration free region has a broad lateral extent, relatively. Thus off-axis viewing is acceptable over a greater range. To accommodate different substrate depths, different NAILs will typically be used, leading to the use of NAIL sets and arrays of NAILs. The NAIL may also be coated to minimize reflections for background or foreground illumination. The NAIL may be fabricated as a compound lens and/or have an objective design to correct for chromatic aberration.

Fig. 4A illustrates a further use of the invention in testing biological or chemical specimens for changes or conditions of optical properties. A substrate 100 has a NAIL lens 102 thereover as above. The substrate may have an insulating or other layer 104 to allow adherence of a specimen 106. The surface of the specimen is located at the zone of focus, typically corresponding to focus zone 54 where any optical properties in ambient or applied transmitted or reflected light can be viewed through the NAIL 102 with enhanced resolution. The substrate may have a semitransparent metal thereon for such purposes as enhanced specimen bonding.

The specimen 106 such as shown in Fig. 4b, can be placed in an environment such as defined by a housing 108 where excitation, such as microwave energy, or a fixed or changing chemical environment can be applied to the specimen 106.

Fig. 5 illustrates the application of the invention to use in viewing specimens 106 on a substrate 116 such as a microscope slide with a cover slip 118 over the

specimen 106. A NAIL lens 120 is placed over the cover slip and the materials are dimensioned to provide a zone of aberration free focus at the specimen 106 as above. A NAIL lens can be placed on the substrate with this same zone of focus as described above.

In Fig. 6 the NAIL of the invention is illustrated in use for the creation and reading of media. In this case, the substrate 130 includes a read or write or read/write medium such as is used in CD, DVD, Minidisk players and recorders. An optical system 132 is shown to illustrate the well-known apparatus for writing and/or reading to and from such media. A NAIL 134 provides a zone of focus at a plane occupied by a layer 136 which is responsive to input laser light (with or without other influences such as a magnetic field) from one version of the system 134 to create a permanent or erasable record in the layer which can be later read by a further version of the system 132.

Figs. 7a - 7d show the results of actual NAIL usage to image a layer of semiconductor structure as might be exemplified by Fig. 2b using a back lighting system 150. Fig. 7a illustrates the image of structure obtained with a normal 5.4X microscope without a NAIL. Figs. 7b and c illustrate the view using a NAIL over the semiconductor substrate. Polysilicon test lines and an N-type diffusion fabricated into the semiconductor at locations 140 and 142 respectively are clearly shown. Fig. 7d shows a linear scan across the image of Fig. 7c indicating the sharp resolution at an enhanced total magnification of approximately 96X.

The invention is also useful in examining the junction in semiconductor devices formed between silicon

and an insulator in Silicon-on-Insulator fabrication by placing the junction at the zone of focus and aberration free viewing as shown in Fig. 8. Here the layer 160 represents a boundary between semiconductor material 162 and insulator 164. A NAIL 166 allows enhanced inspection of this boundary. In the case of a semiconductor material as the NAIL and/or substrate, the materials of Si, Ge, SiGe, GaAs, GaSb, GaP, InP, GaN or combinations including combination of the basic atoms in tertiarary or higher structures are useful among others.

The invention is also useful in Raman spectroscopy for detecting Raman scattering from within substrates. Fig. 9a - 9b illustrate an array 170 of NAILs 172 according to the invention on a substrate 174. A single objective lens 176 can then be used with a plurality of the NAILs 172. This provides the advantage of a broader field of view. Additionally, by using NAILs 172 of different geometry's, different depths within substrate 174 can be viewed in aberration free focus. Fig. 10 illustrates a set of NAILs 180, 182 ... 184, typically of the same or similar radius, useful in practicing the invention.

In practicing the invention with an optical system of external lenses, such as exemplified by Fig. 1, overall correction of chromatic aberration can be accomplished by the combined optical properties of the NAIL and other system optics. The invention utilizing correction of chromatic aberration also allows broad spectral correction at IR wavelength for thermal imaging, and near-IR wavelengths for visual inspection of semiconductor circuits and devices.

In The Claims

1. A lens for use in a system for viewing or imaging light into or from a substrate of a material through a surface thereof with an expanded numerical aperture comprising:

a lens having a first surface matching the surface of said substrate and a second surface in convex shape;

said lens having a zone of focus, when the first surface thereof is in contact with said substrate surface, within said substrate;

said viewing or imaging light passing through said convex surface with phase fronts geometrically distinct from said convex surface shape.

2. The lens of claim 1 wherein said viewing or imaging light includes rays in the IR, visible, or UV spectrum.

3. The lens of claim 1 wherein said lens is a compound lens for chromatic aberration correction.

4. The lens of claim 1 wherein the index of refraction of the lens and the substrate are matched.

5. The lens of claim 1 wherein said lens and said substrate are integrally formed of substantially the same material.

6. The lens of claim 1 wherein one or both of the said substrate or lens are fabricated of a semiconductor material.

7. The lens of claim 6 wherein said semiconductor material is selected from the group consisting essentially of Si, Ge, SiGe, GaAs, GaSb, GaP, InP, GaN or combinations thereof.

8. The lens of claim 1 wherein said substrate contains fabricated structure including devices and circuits located at or near said zone of focus.

9. The lens of claim 1 wherein said substrate contains fabricated structure that emits blackbody radiation at or near said zone of focus, thereby allowing for thermal imaging.

10. The lens of claim 1 wherein said substrate is a Silicon-on-Insulator wafer with a boundary at said zone of focus.

11. The lens of claim 1 wherein said substrate includes a semitransparent metal on a surface thereof at said zone of focus.

12. The lens of claim 1 wherein said convex surface shape is spherical.

13. The lens of claim 12 wherein said lens has a radius of curvature, R, and said material has an index of refraction, n, and said zone of focus occurs at a radius of R/n from the geometrical center of said spherical convex surface.

14. The lens of claim 13 wherein said zone of focus is aberration corrected and extends over a range of radii such that a surface cutting said zone orthogonal to the radius has a region of aberration corrected focus.

15. The lens of claim 14 wherein said focus zone has said cutting surface parallel to said substrate surface.

16. An optical system including one or more lenses in combination with one or more lenses of claim 1 provide correction of chromatic aberration.

17. An optical system including one or more lenses of claim 1 responsive to light from said lens to provide imaging thereof with enhanced resolution of objects at said zone of focus.

18. The optical system of claim 17 further including an array of said lenses.

19. The optical system of claim 17 further including an objective lens or set of lenses for adjusting the depth of the said zone of focus in said substrate.

20. The optical system of claim 17 wherein said imaging system has an objective and an exit lens whose principle points are separated by a distance, d, according to the relationship $d = f_1 + f_2 - f_1^2/R(n+1/n)$, R being a lens radius and n an index of refraction for said lens and substrate.

21. The optical system of claim 17 wherein said optical system provides broad spectral chromatic aberration correction at IR wavelengths for thermal imaging.

22. The optical system of claim 17 wherein said optical system provides for operation at near-IR wavelengths for through the substrate visual inspection of semiconductor circuits and devices.

23. The optical system of claim 17 including a system for measuring Raman scattering.

24. The optical system of claim 17 including a system for time-resolved measurements.

25. The lens of claim 1 further including a second surface to said substrate adapted for placement of a specimen thereon and wherein said zone of focus is at or near said second surface.

26. The lens of claim 25 further including a system for testing said specimen in a predetermined environment.

27. The lens of claim 25 further including a source of specimen excitation.

28. The lens of claim 1 wherein said substrate includes a specimen holder having a top surface in said zone of focus and a cover slip thereover.

29. The lens of claim 1 further including a substrate responsive to illumination of a predetermined

characteristic at said zone of focus for producing a readable record of the presence of said illumination.

30. The lens of claim 29 further including a read/write system having said substrate as a recordable and readable medium.

31. The lens of claim 1 further including a record retrieval system for reading data at said zone of focus and wherein said substrate is a data medium.

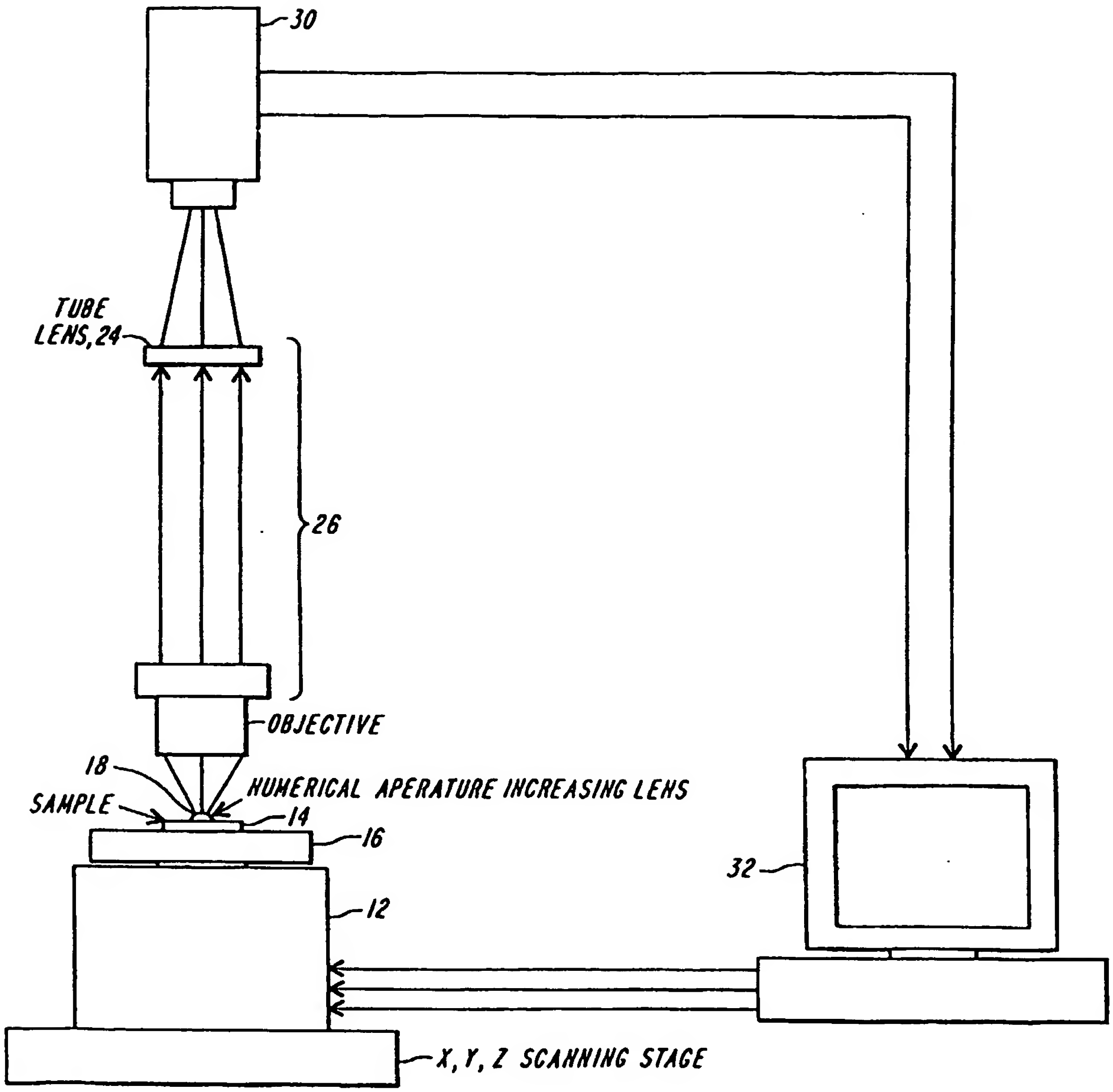
30
TUBE LENS, 24
26
OBJECTIVE
18
NUMERICAL APERATURE INCREASING LENS
SAMPLE
14
16
32
12
X, Y, Z SCANNING STAGE

FIG. 1

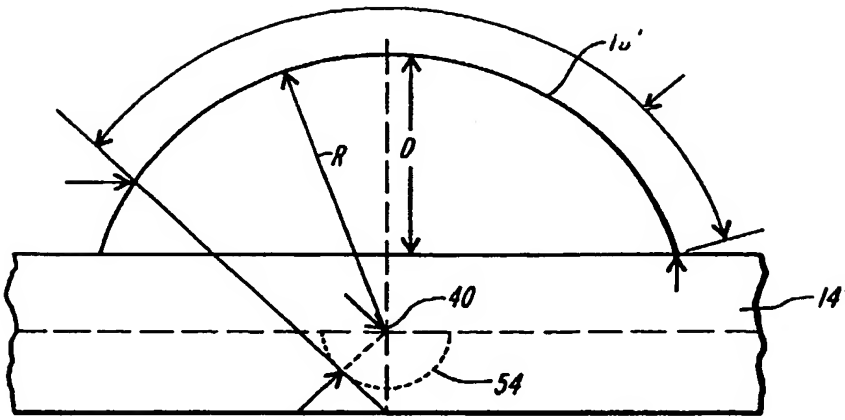

FIG. 2A

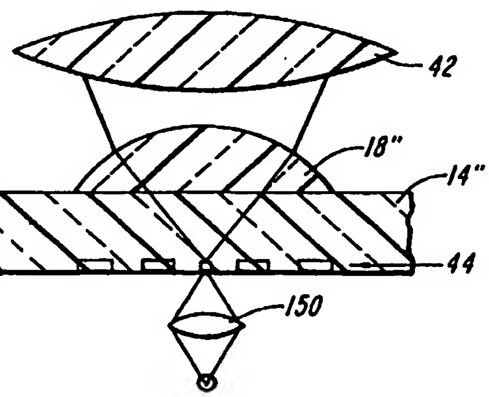

FIG. 2B

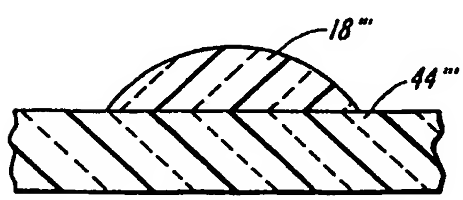

FIG. 2C

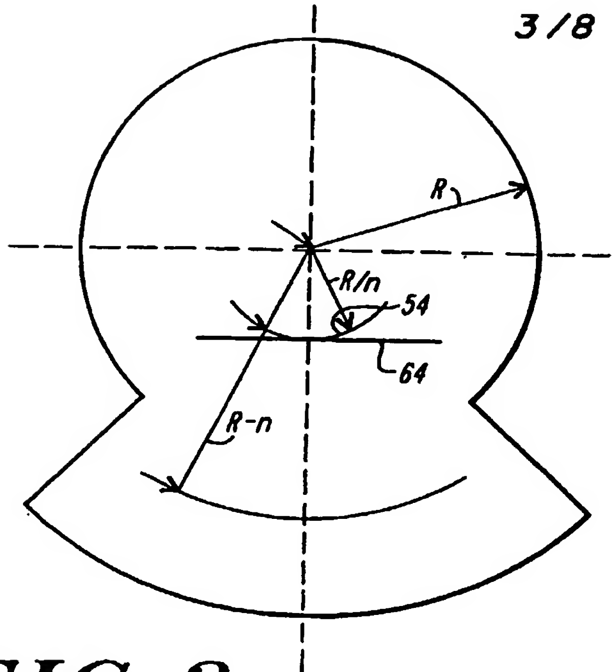

FIG. 3

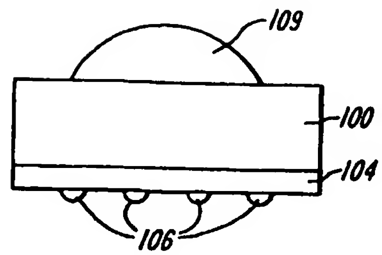

FIG. 4A

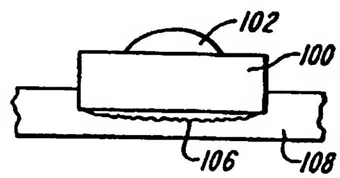

FIG. 4B

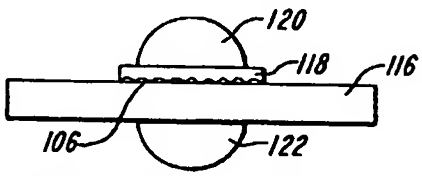

FIG. 5

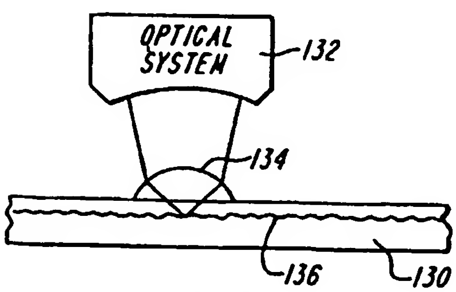

FIG. 6

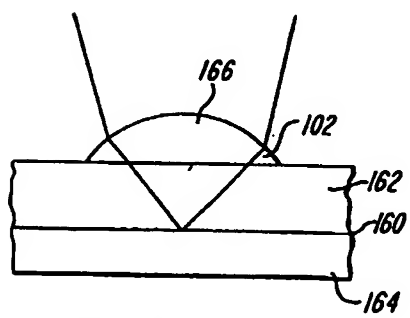

FIG. 8

FIG. 7A

FIG. 7B

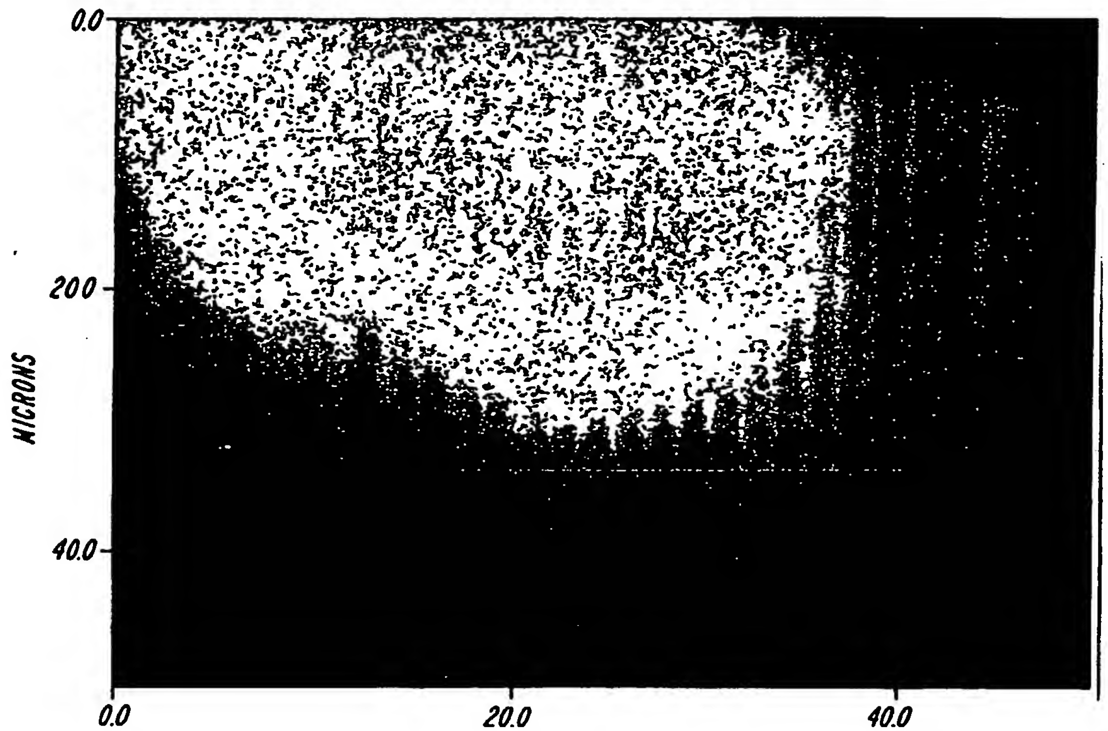

FIG. 7C

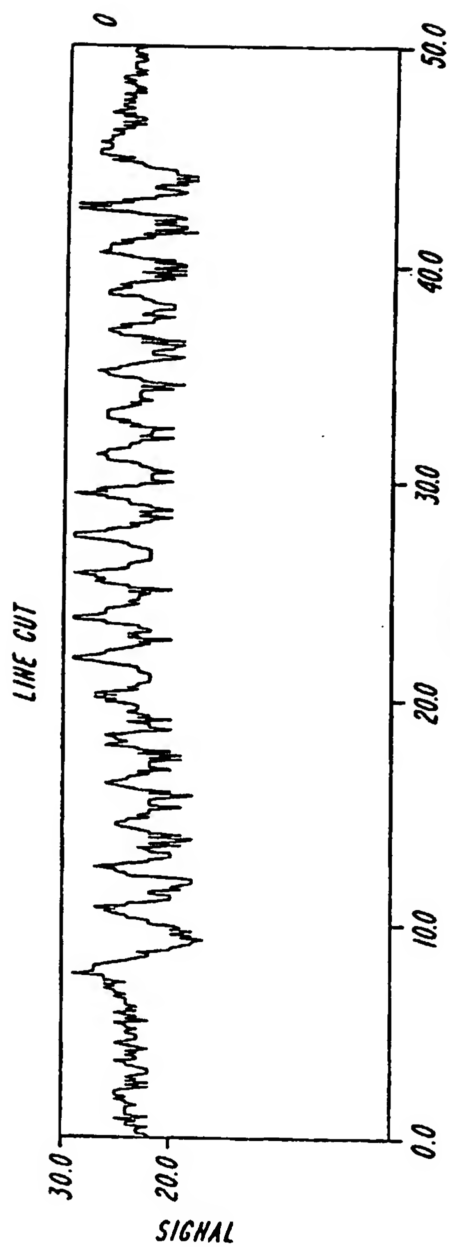

FIG. 7D

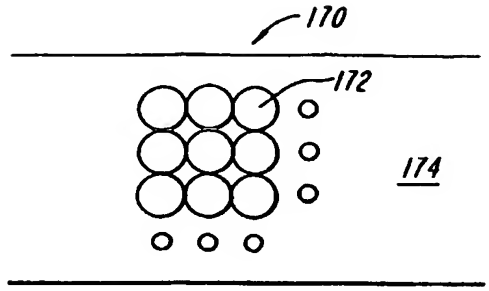

FIG. 9A

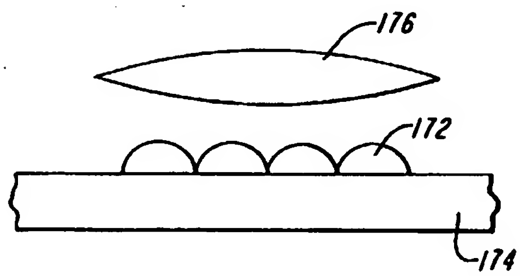

FIG. 9B

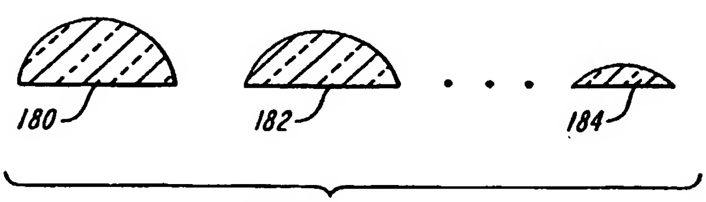

FIG. 10

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US00/40253

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) :G02B 03/00; G11B 07/00
US CL :359/642, 664; 369/112
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 359/642, 664; 369/112, 44.22, 44.14

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

USPAT, JPO, EPO, DERWENT, IBM TDB
search terms: (sil and microscope), (numerical adj3 aperture), (convex adj3 (lens or surface))

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5,497,359 A (MAMIN et al.) 05 March 1996 (05.03.1996), col. 5, line 29 through col. 8, line 28.	1, 2, 8, 10, 17, 18, 25-27, 29-31
A	US 5,764,613 A (YAMAMOTO et al.) 09 June 1998 (09.06.1998).	1-31

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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Date of the actual completion of the international search	Date of mailing of the international search report
09 OCTOBER 2000	14 NOV 2000

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